013660

Shadowgraph Observations of the Flow Past a Sphere and a Vertical Cylinder in a Density Stratified Liquid

Technical Report EM-71-3

WALTER DEBLER
PETER FITZGERALD

December 1971

Office of Naval Research
Contract N00014-67-A-0181-0008

Under the Direction of
James W. Daily
Walter Debler

THE UNIVERSITY OF MICHIGAN 1817
Department of Engineering Mechanics
Fluid Mechanics Section

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

ABSTRACT

Shadowgraphs were made of the flow past a sphere in water that was vertically stratified with sodium chloride. The intent was to explore the flow patterns at low Reynolds numbers with particular emphasis on any asymmetries due to the stratification. The shadowgraphs recorded three-dimensional phenomena and the visualization was in agreement with that obtained with dye inserted at the sphere. Thus the optical technique is useful even though the lack of two-dimensionality prohibits the drawing of any quantitative conclusions.

Qualitatively one observes, at low Reynolds numbers, that the stratified fluid flows <u>around</u> the sphere. The extent of latitudes over which this horizontal flow is present decreases as the Reynolds number increases. At Reyndolds numbers greater than 100, depending on the stratification, the flow continues to move over the sphere without separation. Some flow interactions may occur downstream of the sphere to produce an eddy which with increasing Reynolds number ceases. Ultimately a Reynolds number is reached at which separation occurs at the rear of the sphere. The wake region increases with increasing Reynolds number.

Tests were also conducted on vertical circular cylinders in the stratified water. The intent was to see if the stratification would inhibit the occurance of a turbulent

wake, a three dimensional phenomenon. The preliminary shadowgraphs show a curious perodicity, in the spanwise direction, for the wake in the stratified fluid at a Reynolds number of about 1000.

DESCRIPTION AND DISCUSSION OF SHADOWGRAPHS

A flume for studying the flows of a stratified liquid is available in the laboratories of the Department of Engineering Mechanics. It is constructed out of non-corrosive materials to facilitate experiments with water - NaCl solutions. This flume and the device which permits the automatic filling of the flume are described in Appendix A. In addition there is a towing carriage which is pulled along the flume by a cable that is driven by an electric motor and a mechanical speed transmission. The construction of the towing carriage and drive system is such that no visable vibrations of the body being towed can be observed.

A one inch (2.54 cm) sphere which was made of stainless steel was attached to a horizontal strut or "stinger" that was eight inches long. The size of this support strut can be seen in the photographs which follow. It is believed that its diameter (1/16 inch tapering to 1/8 inch) was small enough so as not to affect the results. This strut was attached to a vertical rod which was fastened to the towing carriage.

The shadowgraph images were constructed by placing a point light source (Sylvania concentrated arc lamp C25) at the focal point of an aerial camera (36 inch, f8). The parallel light beam was shone through the plexiglas side walls of the flume in a direction perpendicular to the direction of towing. The image was viewed on a translucent sheet of Mylar and photographs of these images were taken. A hack-saw blade was included in some of the photographs to permit a scaling of the pictures. Both the light source and the screen were movable so that photographs at various points along the length of the flume could be taken.

The body was initially located at one end of the flume and the towing speed was adjusted for the lowest value desired for the particular test series. Photographs of the shadowgraph images were taken and the visual observations were recorded. When sufficient photographs had been taken the speed of the towing carriage was increased to the next desired value. Some time was allowed to elapse before the images were recorded to permit the decay of any transients. After the towing carriage reached the end of the flume, the body was removed and the carriage was returned to its starting position. Additional runs could then be made with the knowledge that the stratification may have been disturbed slightly by the first tests.

At the very lowest speeds (i.e., Reynolds numbers)

there was nothing to be seen on the screen. With increasing speeds two horizontal lines appeared to be attached to the top and bottom of the sphere. Figure 1a illustrates this. On the basis of previously performed experiments which used dye as the measure of visualization it was concluded that the fluid was not flowing over and under the sphere to any great degree. Rather it was flowing around the sphere. This is not an unexpected result of stratification. The consequence of this observation is that the occurance of an attached vortex to sphere, cf. Taneda (1956), could be significantly inhibited. At higher Reynolds numbers, the vertical extent of the horizontal lines in the photographs decreases. This is taken to mean that the latitudes over which the flow is horizontally around the sphere are decreasing. The shadowgraphs (figures 1b, 1c and 1d) also show some downstream waves.

When the Reynolds number had reached a value of about 300, depending upon the degree of stratification originally present, there was no visable wake at the body.

Figures 2a and 2b picture this flow, R = 294 and 326, while figure 2c, R = 482, shows the beginning of separation at the body, the phenomenon that is described by Taneda (1956) and others in a homogeneous fluid. At R = 746 the rear wake has increased in extent considerably.

In order to show whether or not the swirls that were present on the shadowgraphs were peculiar to the

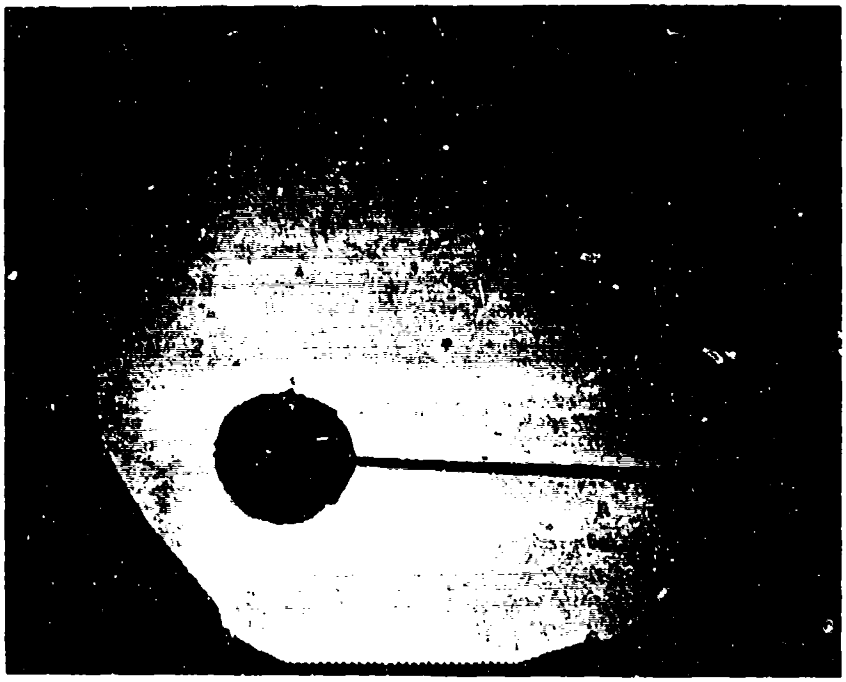


Fig. 1 a.

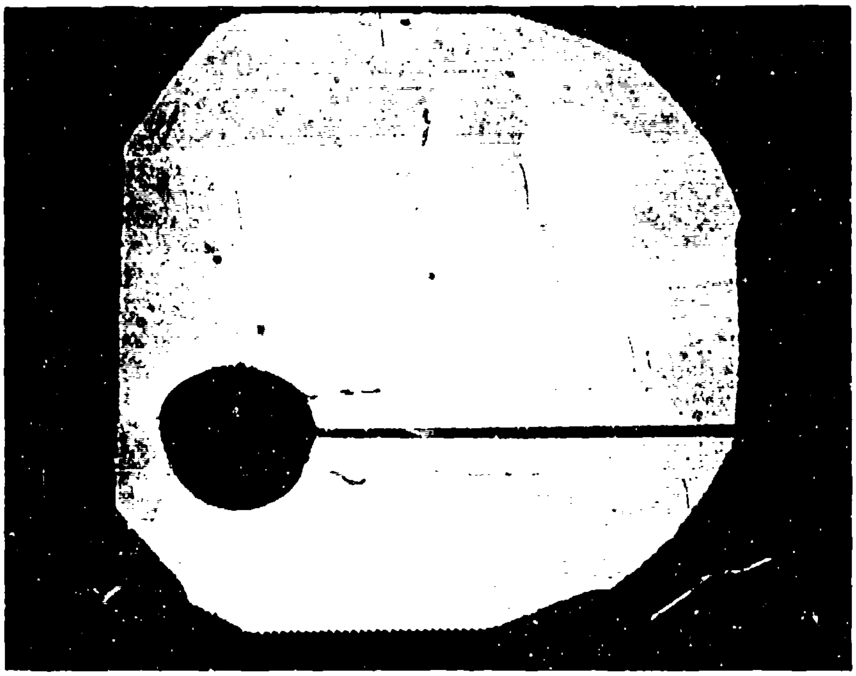


Fig. 1 b.

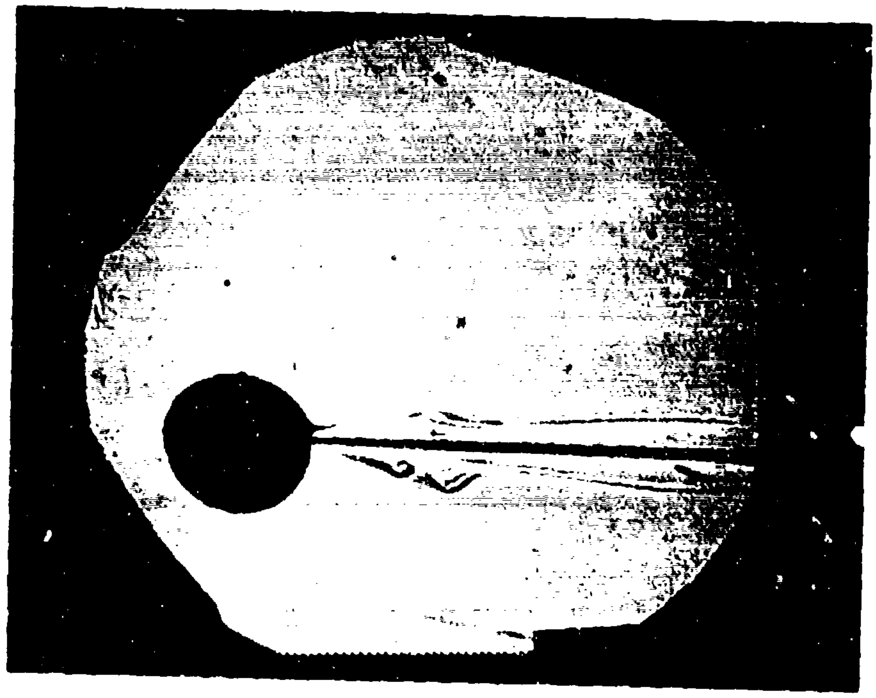


Fig. 1 c.

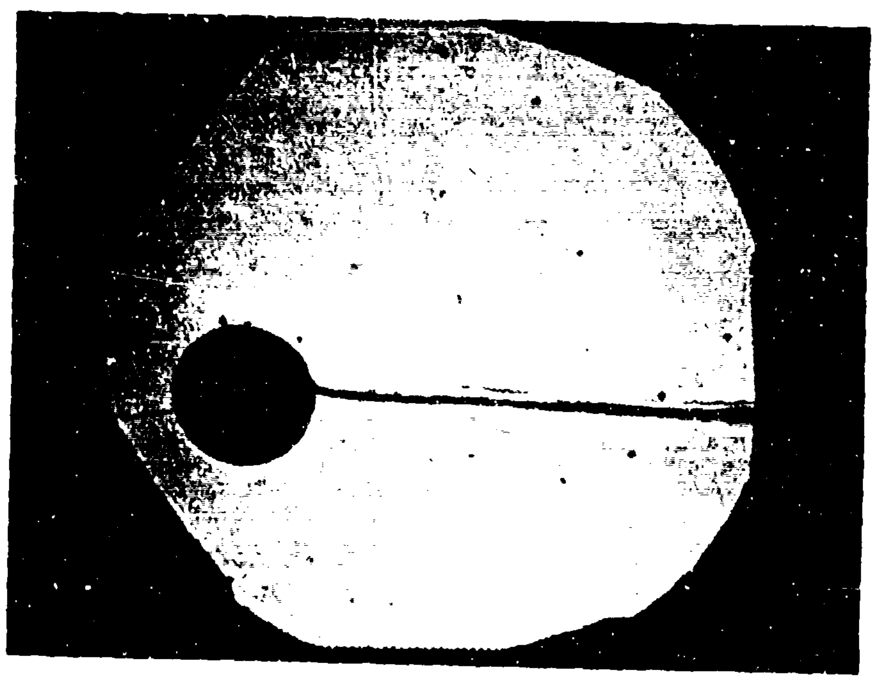


Fig. 1 d.

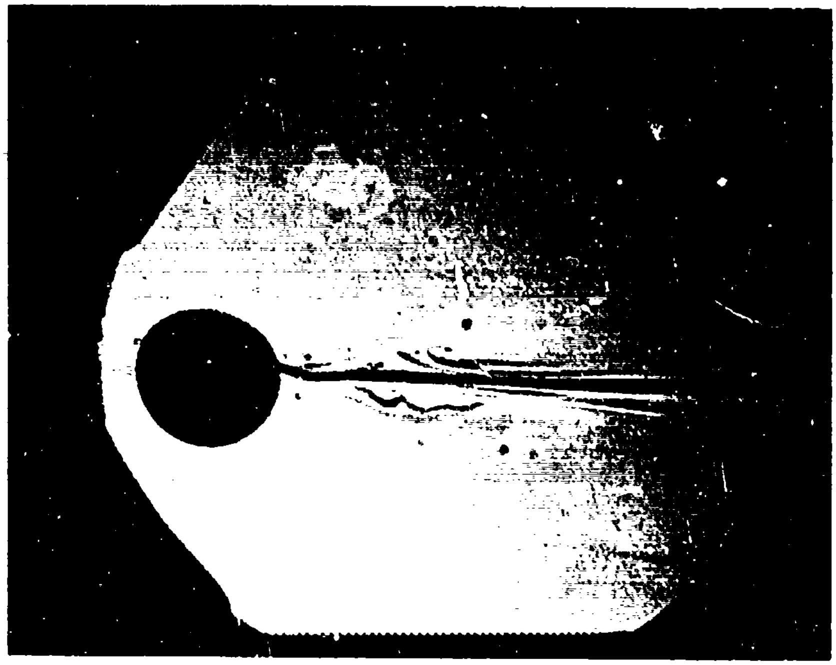


Fig. 2 a.

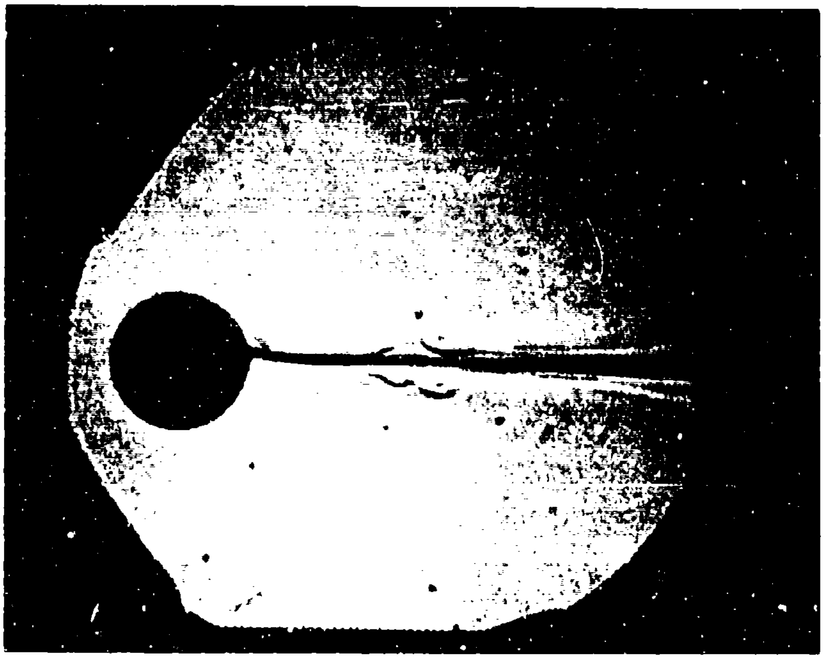


Fig. 2 b.

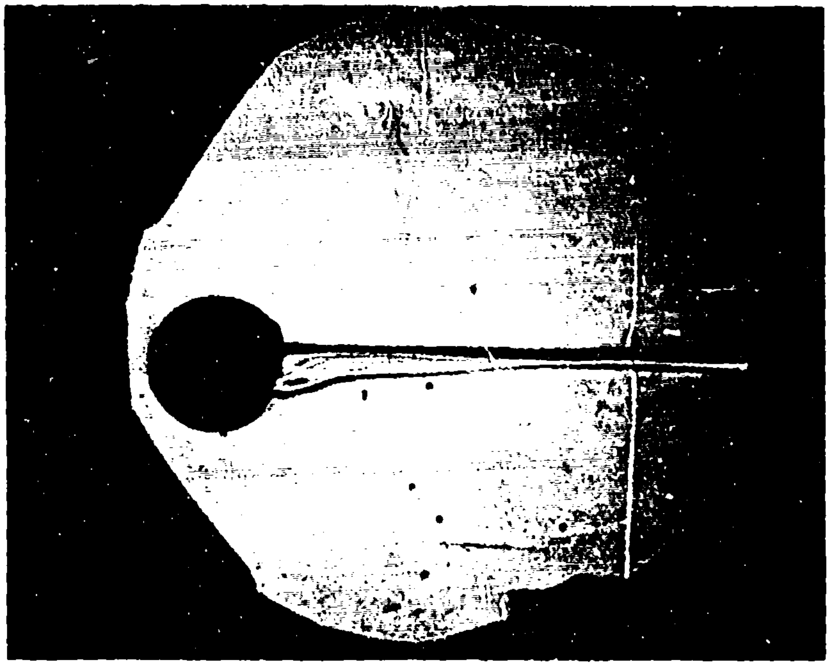


Fig. 2 c.

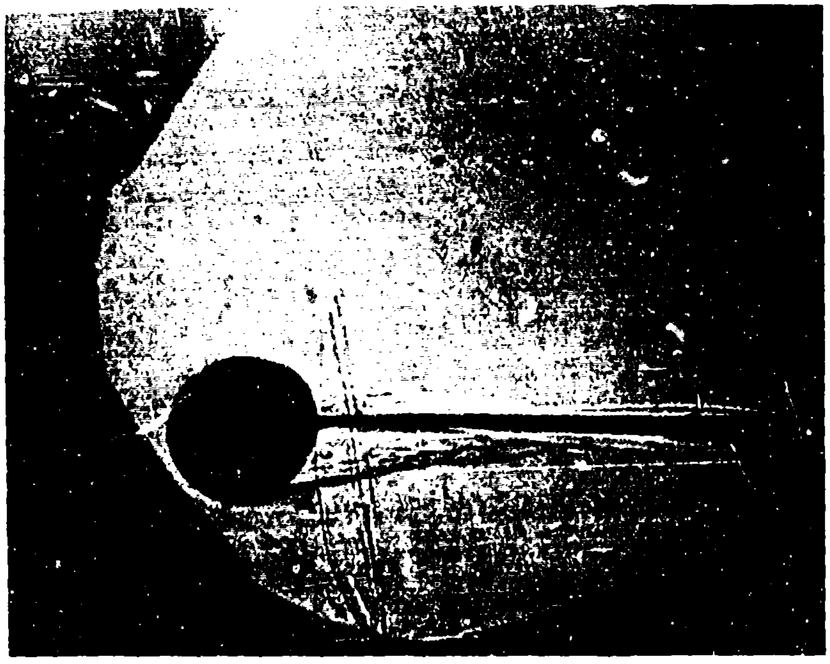


Fig. 2 d.

shadowgraph method, a series of photographs were taken when dye was added to the boundary of the sphere. This was done by dropping on to the sphere small crystals of potasium permanganate. Normally this was done while the sphere was at rest but with practice it could also be done while there was a slow movement. These crystals were dissolved by the fluid flowing past the sphere and gave an indication of the flow pattern. Figures 3a and 3b are an indication of the results. A comparison with figure 1b shows a considerable similarity between the images made by the shadowgraph method and dye. Subsequent illustrations in this report support this observation. The dye method also emphasizes the "two-dimensional" character of the attached vortex, something which is not as obvious from figure 1b. Figures 4a and 4b show the wake and separation regions at R = 416 with the aid of dye. Figure 4a shows a curious separation at the body which could not be guessed from the side view, figure 4b, or a similar shadowgraph, 2b.

Very strong stratifications (i.e., a density difference of 0.01 g/cm^3 in 30.5 cm. of elevation) produced the flow patterns of figures 5a, b, and c. The flow development as a function of Reynolds number is similar to that of weaker stratifications but they do occur at higher values of R.

Dye was also used to make visable the flow at a strong stratification. Figures 6a and 6b illustrate the result. There is a good correspondence with the pattern shown

Fig. 3 a.

Fig. 3 b.

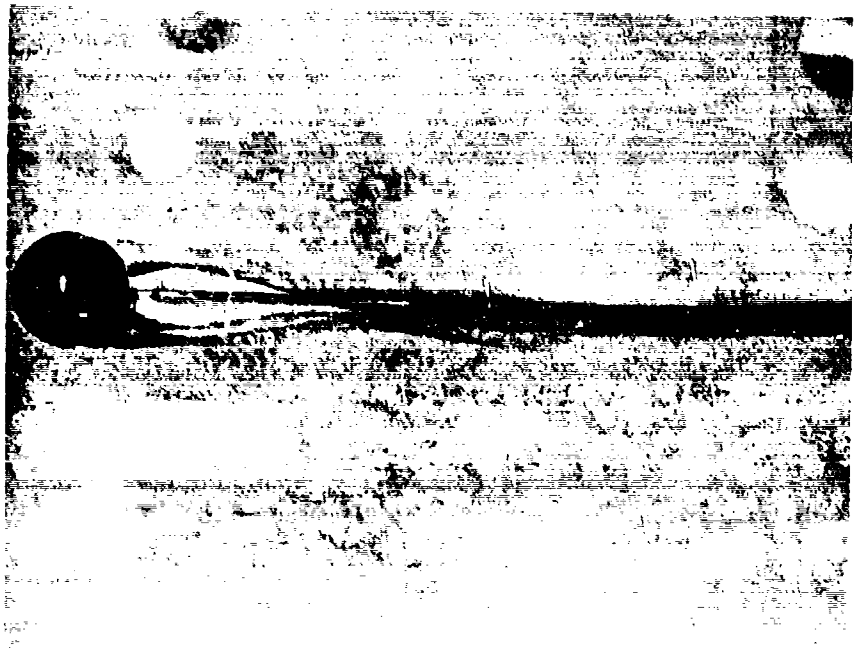


Fig. 4 a.

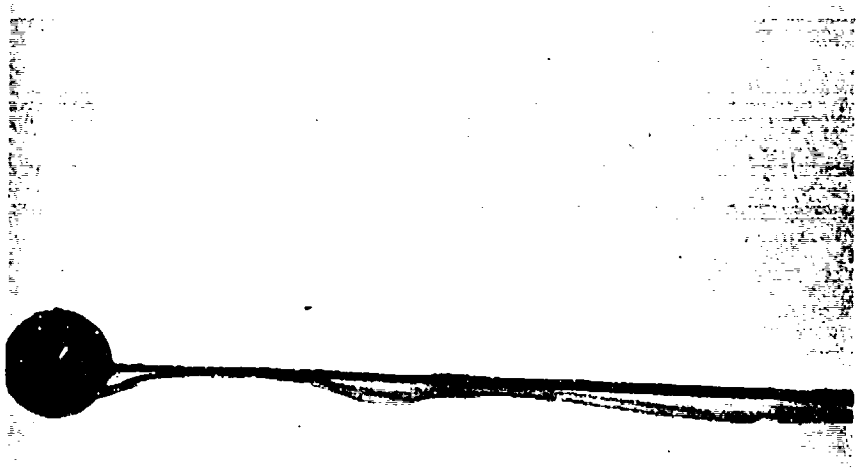


Fig. 4 b.

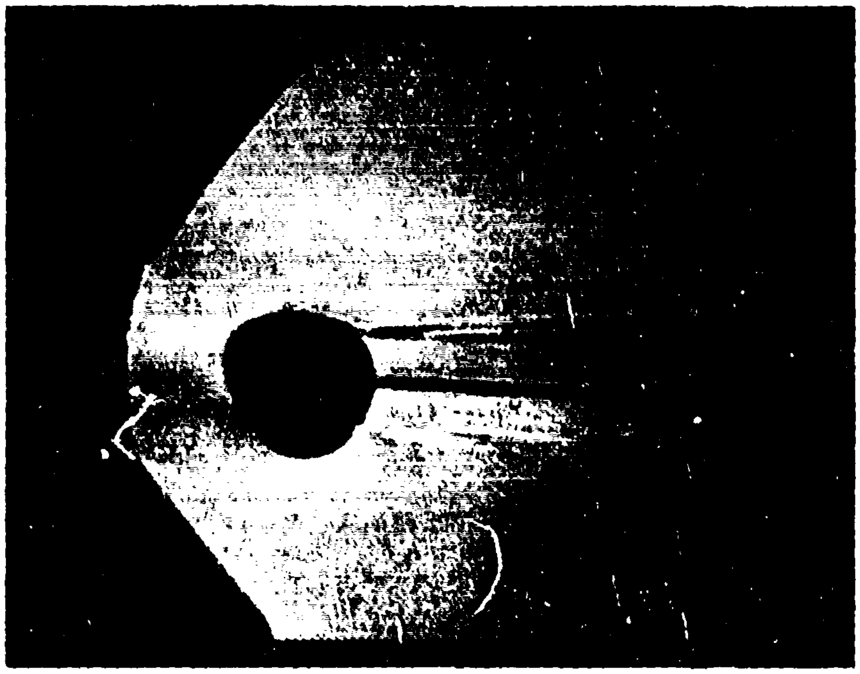


Fig. 5 a.

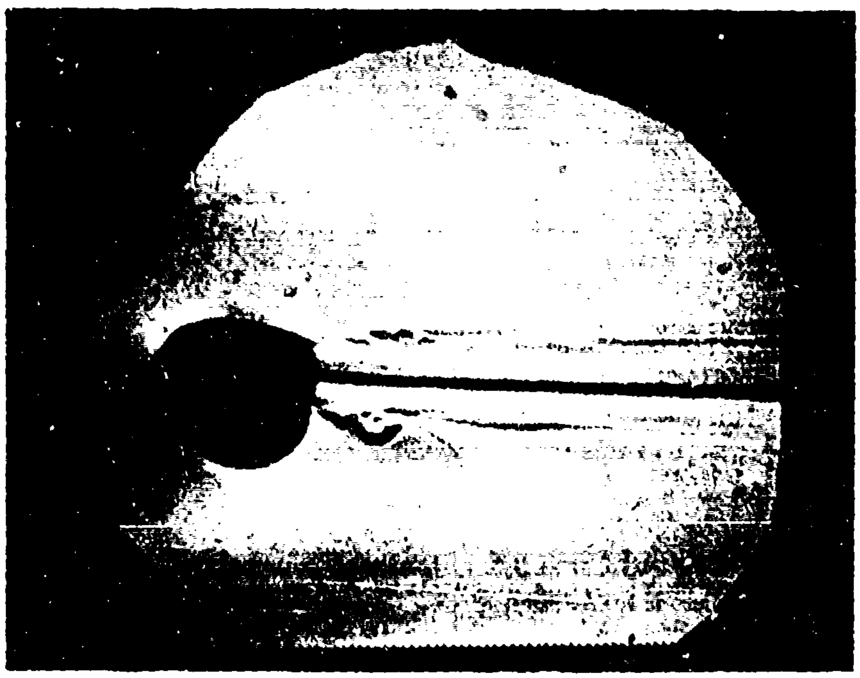


Fig. 5 b.

Fig. 5 c.

in figure 5b. Figures 7a and 7b give results for somewhat higher Reynolds numbers. There is some similarity between figure 7b and figure 5c. Figures 1c and 2b should also be compared with 7b. All of these comparisons indicate that the shadowgraph can give a good indication of a three dimensional flow if the pictures are properly interpreted.

It is believed that the Reynolds and Richardson numbers at which the usual, three-dimensional wake was first observed to occur could be meaningfully plotted. This would delineate the regime where two-dimensional effects due to the stratification were present. This was not done in this report because of the limited data that was available.

A series of experiments was undertaken with vertical, circular cylinders in a vertically stratified fluid. Because of the arrangement of the cylinder no "blocking" was expected. Rather, the tests were intended to indicate whether the suppression of vertical motions due to the stratification would affect the occurance of a turbulent wake, a three dimensional phenomenon, behind the cylinder Some of the exploritory work is shown in figure 8 at a Reynolds number of about 1200. Figures 8a and 8c show the wake close to the cylinder while 8b is a "far field" view. A periodicity in the wake is clearly evident. This structure was unexpected. The work of Fage (1934) and Roshko (1956) suggest that some helical pattern may be in the wake in the spanwise direction as well as a

Fig. 6 a.

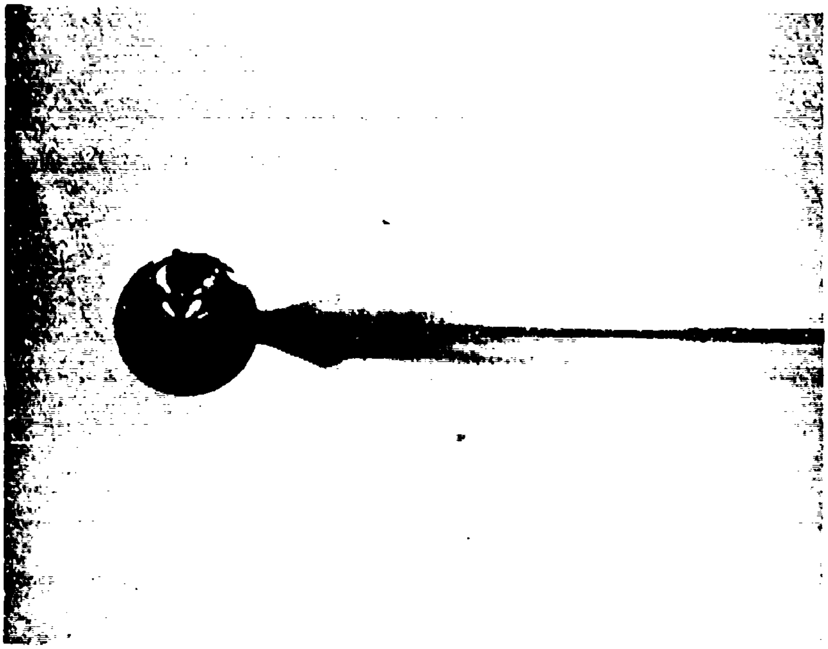


Fig. 6 b.

Fig. 7 a.

Fig. 7 b.

Fig. 8 a.

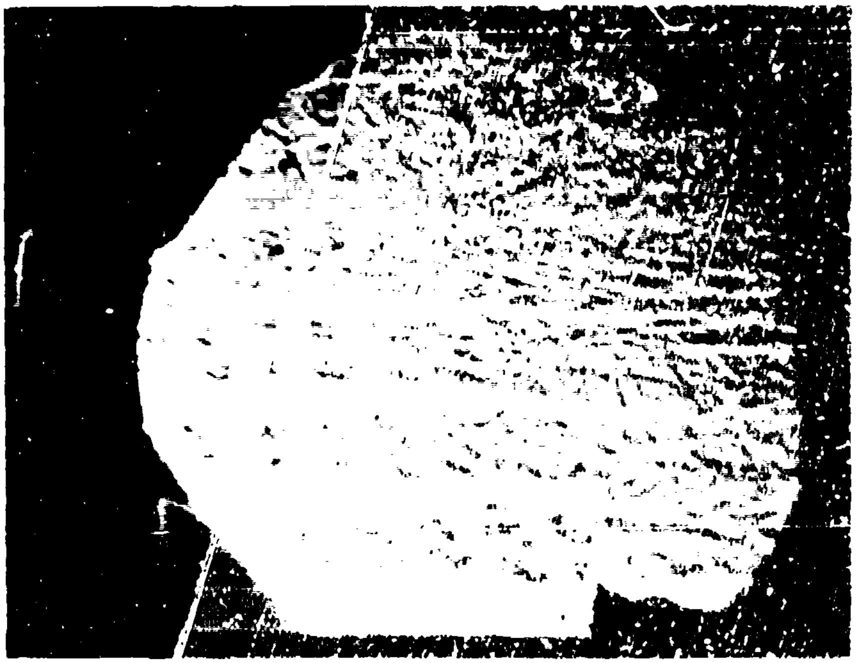


Fig. 8 b.

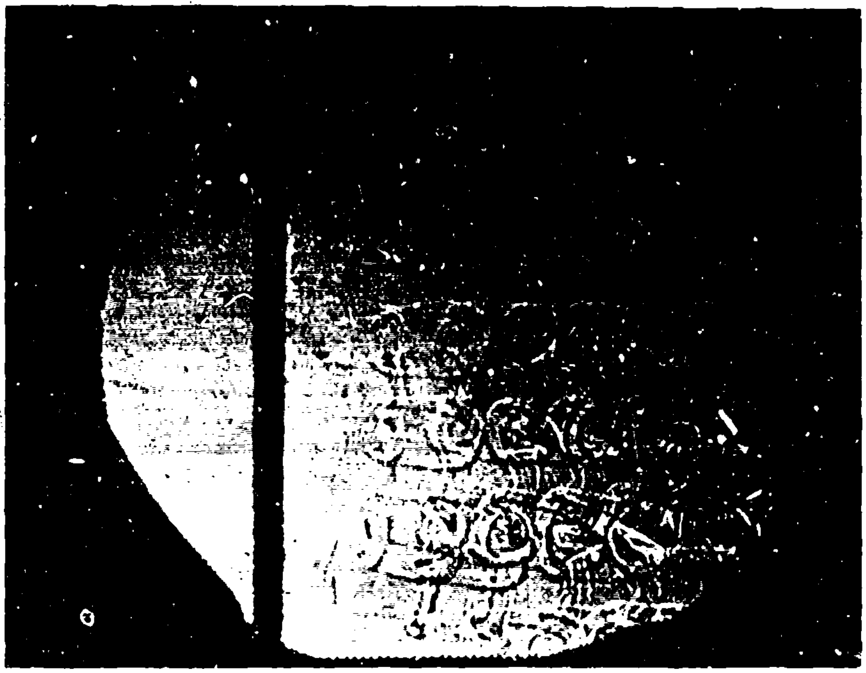


Fig. 8 c.

shift in phase of the Karman vortex street. Both of these observations may be contained in the periodic flow pictured in figure 8.

In figure 9 one can see additional shadowgraphs behind the cylinder. Figures 9a and 9b show wavy, vertical lines which may correspond to the generators of the Karman vortex street pattern (cf. Homann (1936) or most references and text books on advanced fluid mechanics). When the Reynolds number approaches 1000 the spanwise distribution of the wake becomes periodic and remains ordered. This periodicity remains for considerable distances downstream of the cylinder (cf. figures 9c and 9e). A qualitative result is that the frequency of this periodicity increases with R. The conclusion is tentative. Further experiments are planned to explore this periodic flow since it has not been observed to this extent before.

Conclusions

The shadowgraph method of flow visualization is a good technique for giving flow patterns in a stratified fluid even though the flows are not two dimensional. When the method is applied to the flow past a sphere one can observe a continuous transition from a laminar flow around the cylinder (i.e., the plane perpendicular to gravity) to a fully turbulent wake. The stratification inhibits the occurance of the attached vortices on the sphere and separation.

The use of shadowgraph in viewing the flow past a vertical cylinder in a stratified fluid made it easy to

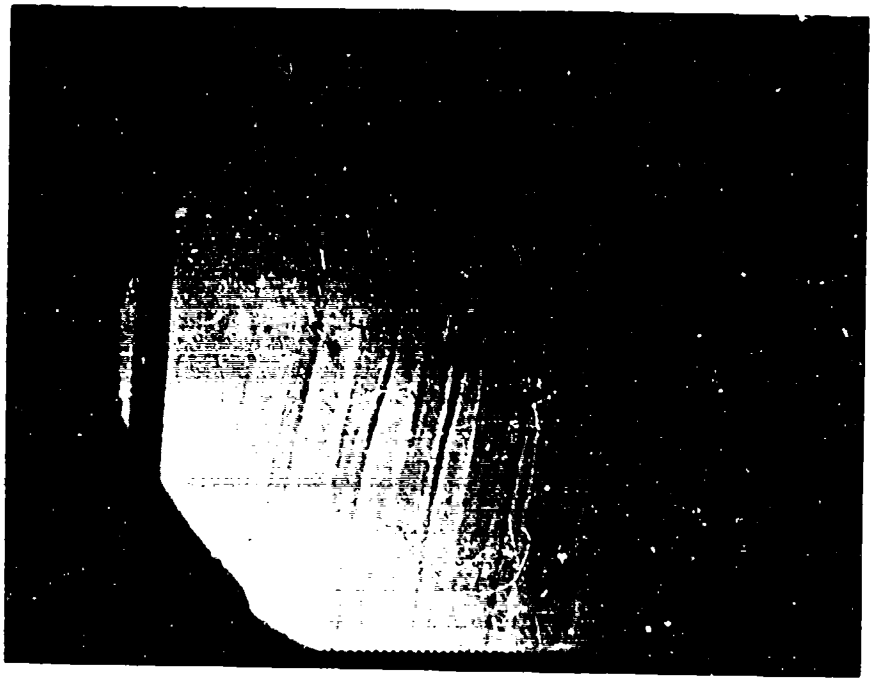


Fig. 9 a.

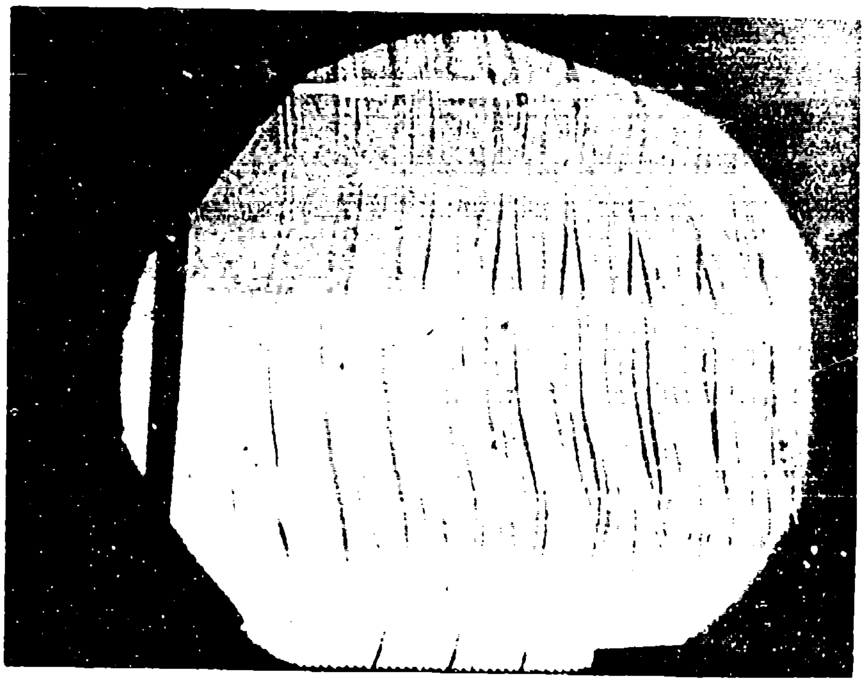


Fig. 9 b.

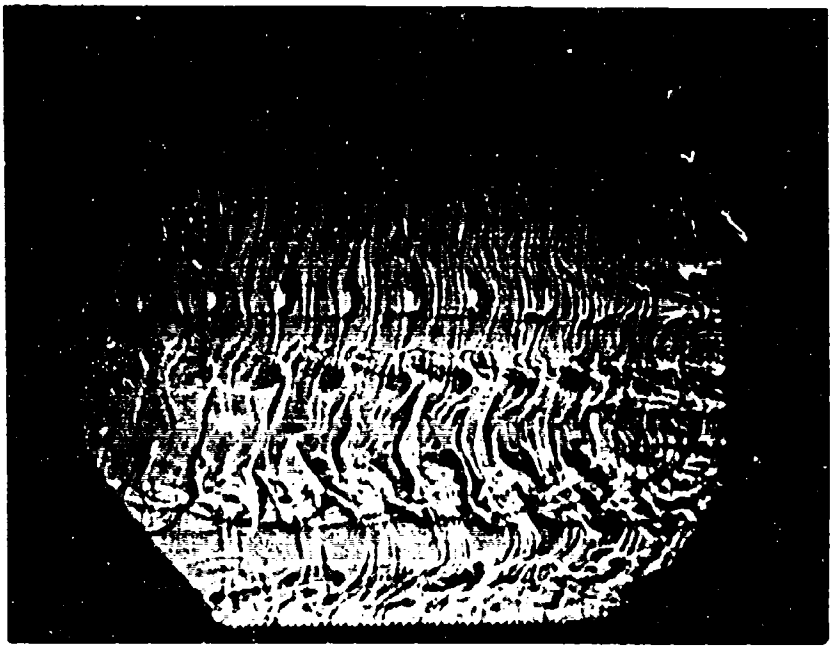


Fig. 9 c.

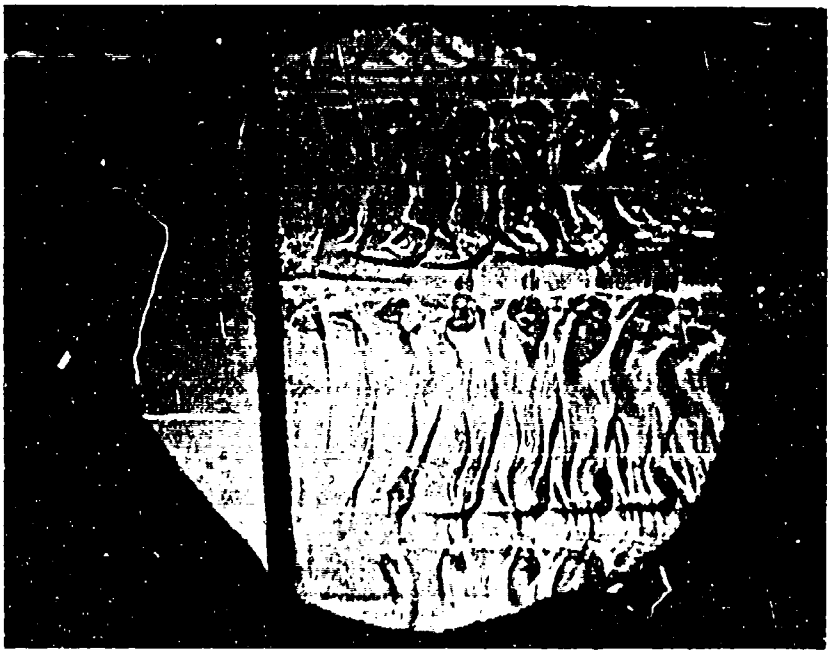


Fig. 9 d.

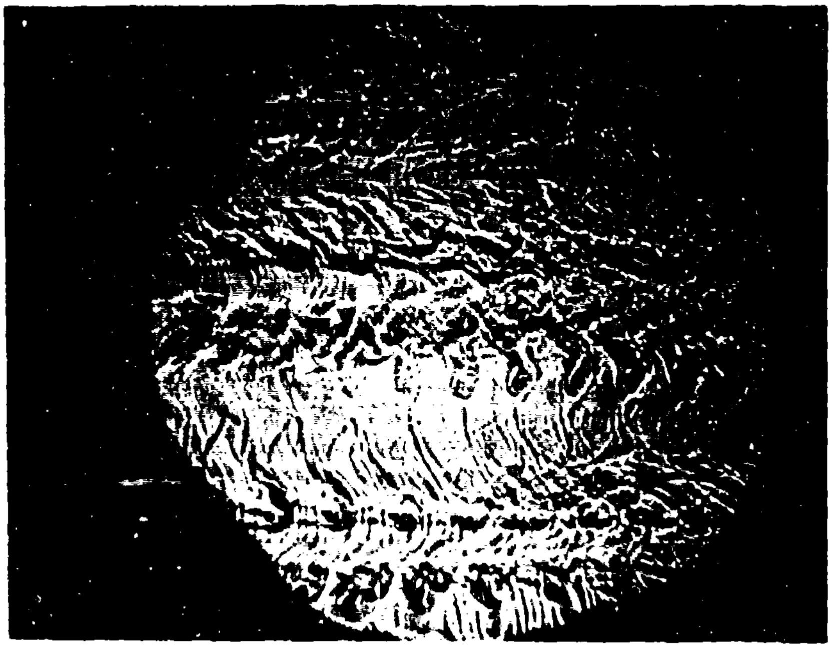


Fig. 9 e.

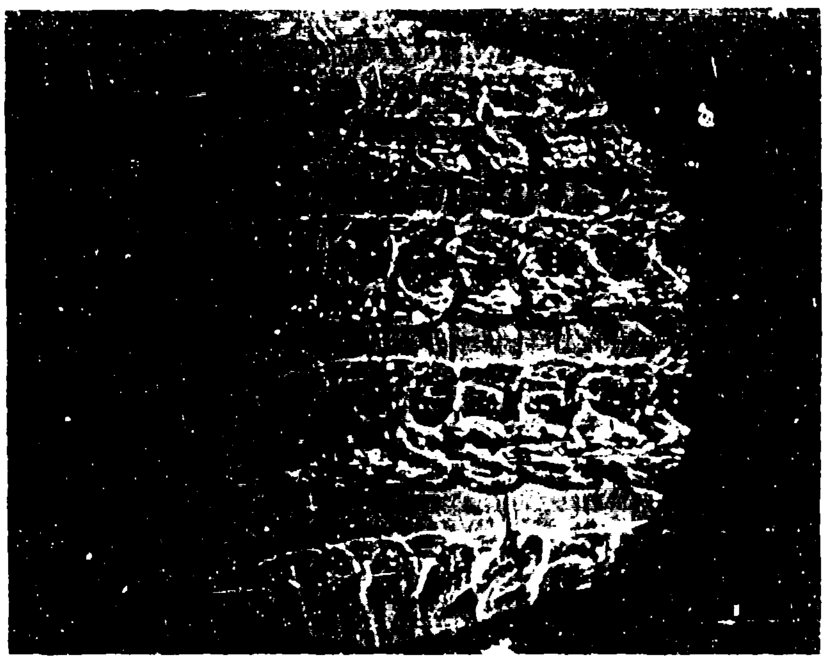


Fig. 9 f.

view vividly the spanwise structure of the wake. A periodicity in the wake was discovered. This phenomenon will receive further study.

ACKNOWLEDGEMENTS

This work was undertaken as a part of the research into stratified flows sponsored by the office of Naval Research under contract N00014-67-A-0181-0008. The development of the filling apparatus described herein was sponsored by the University of Michigan in support of this research.

REFERENCES

Fage, A. (1934), Proc. Royal Soc. A, 144, pp. 381-386.

Homann, F. (1936), Forschung anf dem Gebiete des Ingenieurwesens, 7, pp. 1-10.

Roshko, A. (1954), On the Development of Turbulent Wakes from Vortex Streets, N.A.C.A. Report 1191.

Taneda, S. (1956), Studies on Wake Vortices (III); Experimental investigation of the wake behind a sphere at low Reynolds numbers, Reports of Research Institute of Applied Mechanics, IV, No. 16.

APPENDIX A

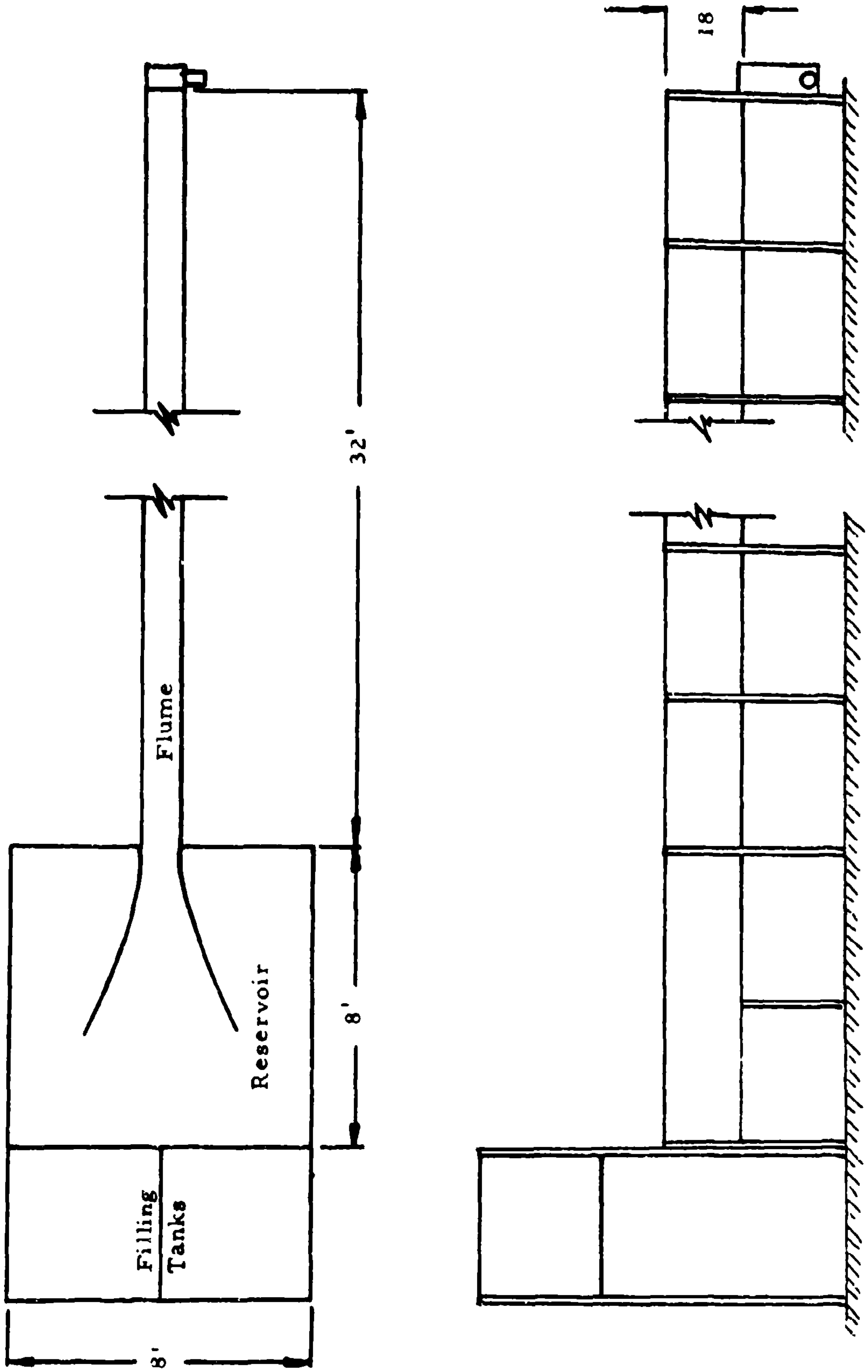
A1. Introduction

A great deterent to the exploration of the phenomena associated with stratified flows of reasonably large scale has been the time necessary to achieve the initial stratification. A variety of ways have been used. Often the fluid is admitted into the flume or tank in discrete layers. These layers are sufficiently thin so that after a period of time a continuous density distribution ensues. Previously these batch methods usually have been manually operated. Someone filled tanks with solutions of various densities and admitted them to the tank which was to be filled at an appropriate rate to prevent undue mixing. Normally a diffusion apparatus was used to restrict the vertical momentum of the incoming fluid. Thereby the incoming fluid was inhibited from mixing with that already in the container. The new liquid would either float upon the existing volume or seep below it, depending on the type of filling process that had been adopted.* A flume-reservoir system as shown in Figure A1 could be filled manually with twelve to eighteen layers, about one inch in height, in ten hours. This required the nearly constant attention of one man during the filling process. An automatic system was desired which would produce not only a superior initial stratification but also eliminate the tedium associated with the existing filling method.

The method discussed in this report is a variation of that produced by Dr. T. B. Benjamin. He varied the amount of sodium chloride (hereafter referred to as salt) which he added by progressively changing the fraction of time which he allowed a saline solution to be admitted to a given volume of liquid that was added cyclically to his experimental vessel.

---

*Same systems introduced progressively denser solutions from below while others floated progressively lighter solutions from above.



Flume-Reservoir System

Figure A1

Other methods for filling have been proposed. One such technique is to fill two reservoirs; one with fresh water and the other with salt water. They are interconnected and liquid is drawn off from the more saline tank in which a mixer is operating. Fresh water enters the saline tank and is mixed with the contents continuously changing the density that is drawn off to the test container. The density of the efflux varies logarithmic with time so that a linear density distribution can be achieved only approximately or with some compensating system.

Others have suggested that a flume can be filled rapidly with two distinct layers. If a suitable obstacle is towed horizontally, along and through the interface between the layers, a nearly linear density (salinity) gradient will result.

Both of the latter methods have as their advantage simplicity and possibly speed. The system described in this report contains a number of mechanical, electrical and electronic components. It will fill the system shown in Figure A1 is approximately eight hours with about 100 layers of liquid. A linear density variation can be achieved now and a minor alteration would result in an arbitrary stable density distribution. Moreover, successive layers of the liquid can be dyed automatically to display the flow patters that occur in the experiments which are conducted. This ability to dye the layers seems to be a principal and significant advantage of the present system over the others hereafter proposed.

A2. Description of the System

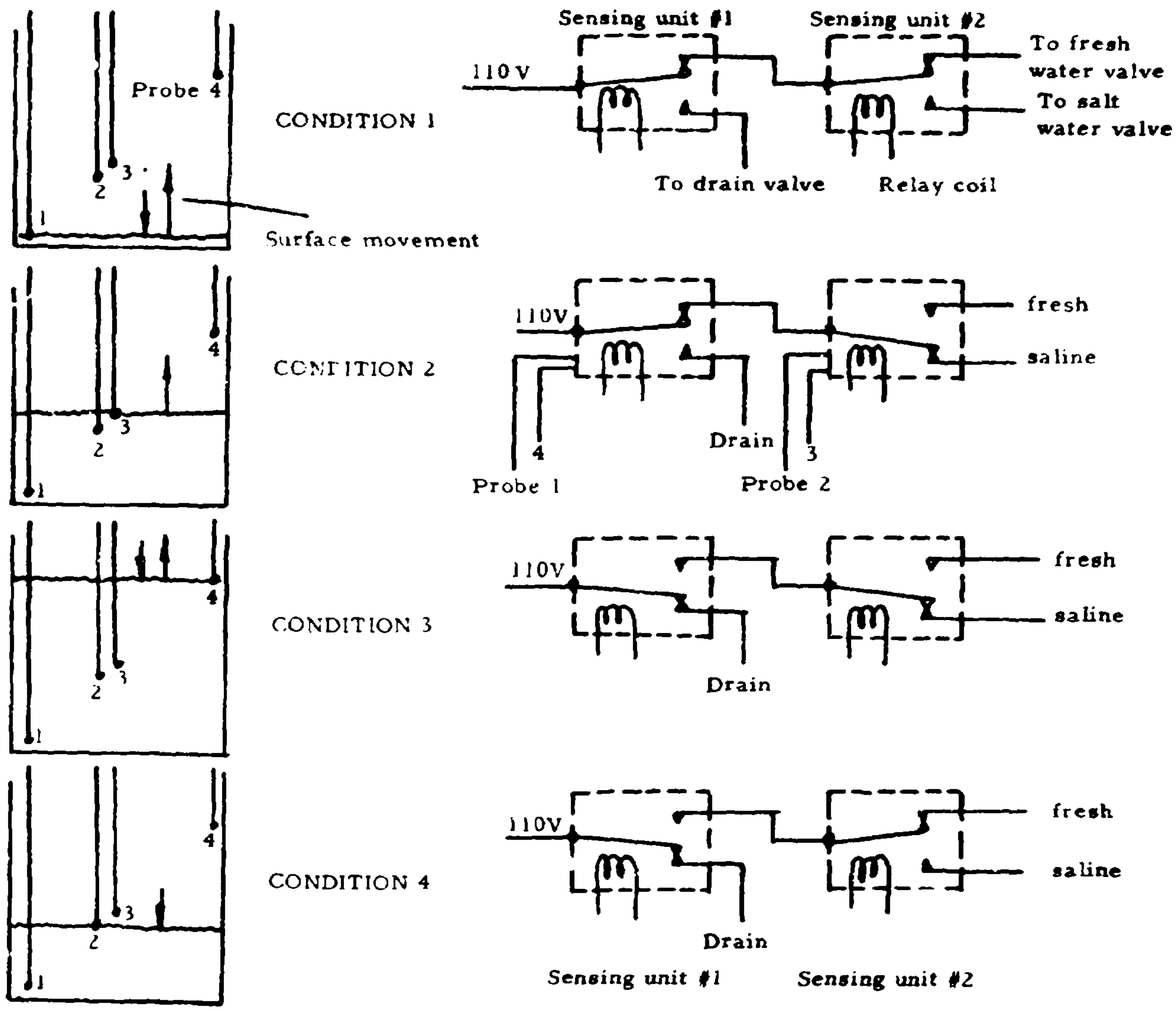
A2.1. Saline-solution metering system

A plastic box with a volume of one cubic foot is filled continually and emptied into the flume-reservoir system. If this system is filled to a height of 12 inches, a total of 96 cubic feet of liquid must be added. Accordingly this will require that the plastic

box be filled 96 times. This is done in a manner that can be described conveniently with Figure A2.

Fresh water is admitted at the beginning of a cycle, Condition 1. When the liquid reaches the level of probe 3, the fresh water is stopped and salt water begins to flow into the plastic tank, Condition 2. The salt water is admitted at the top of the tank in a swirling motion to facilitate the mixing process with the fresh water. The filling process continues until probe 4 is submerged when the salt water port is closed, stopping all filling. Subsequently a drain valve is opened, thereby allowing the solutions to enter the flume. This is Condition 3. The plastic measuring box is drained until probes 3 and 2 are uncovered. This resets their sensing cycles, a matter which will be discussed anon. The draining of the tank continues until probe 1 is bared at which time the cycle begins again with the influx of fresh water.

Probes 1-4 are connected to two level sensors similar to those described in General Electric's Application Note 201.14 (3/66). This circuit as well as a desirable modification for this application are shown in Appendix 3. Briefly the logic of the system is as follows. When probe 1 is bared the relay of sensing unit 1 is opened, cf. Figure A2. In this state electricity flows to the relay of sensing unit 2 and subsequently to a solenoid valve that admits fresh water to the measuring tank when it is activated. When the liquid reaches probe 2 nothing transpires since this probe is attached to the second sensing unit whose relay has been deactivated previously. But when the liquid level reaches probe 3 the relay in sensing unit 2 is activated, closing, and the electrical power is switched from the solenoid valve for fresh water to that for the saline solution. The fresh water valve closes and the salt water valve opens. Figure A2 shows this situation as Condition 2. The salt solution flows into the measuring tank until the level of the liquid reaches



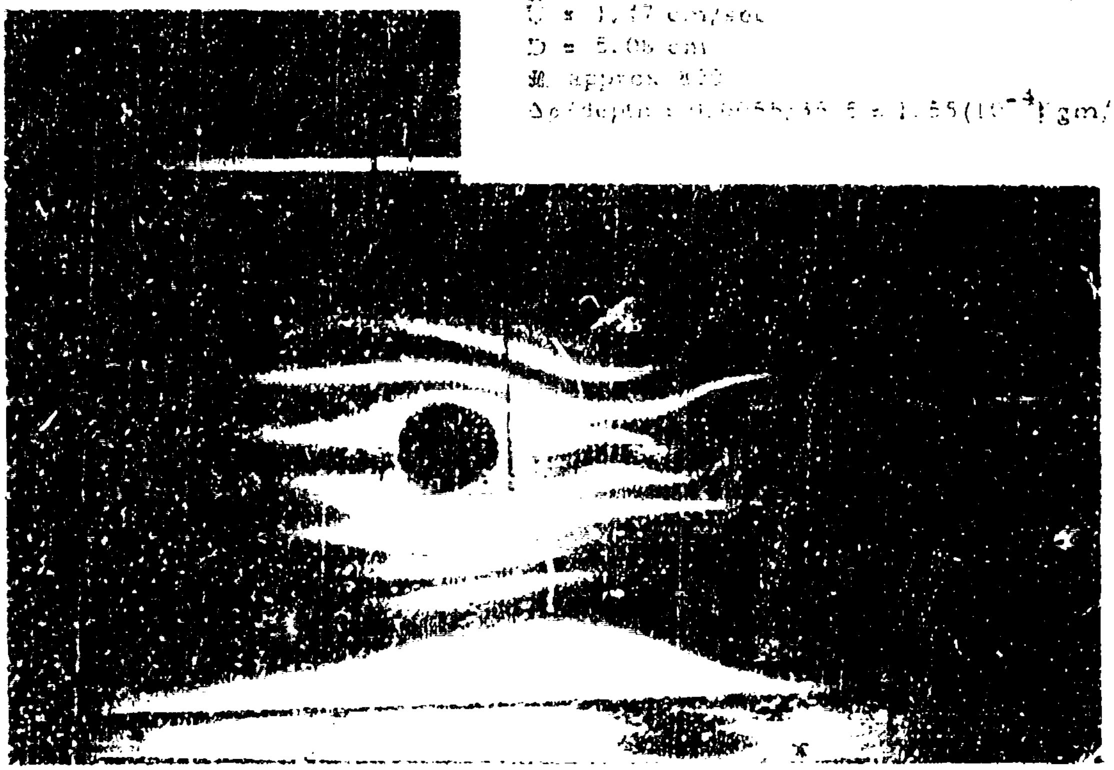
Sequence of relay positions for various measuring tank conditions

Figure A2

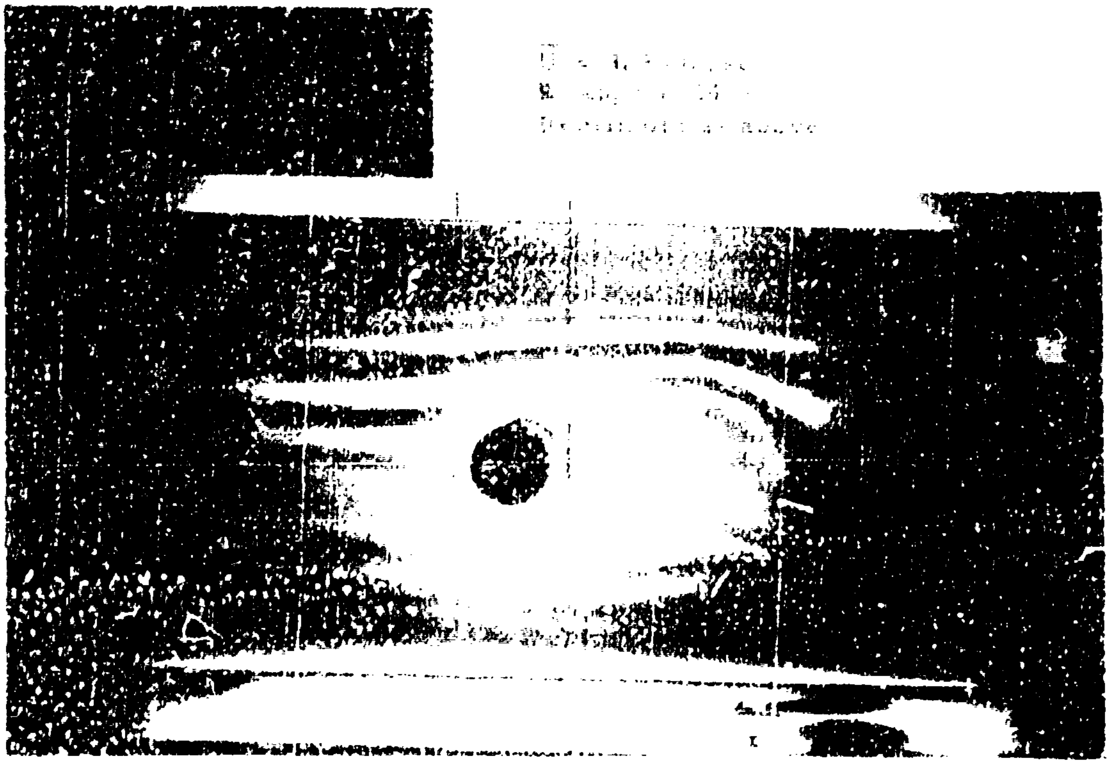
probe 4. This sensor is connected to sensing unit 1. The relay of this unit is activated and the electrical power is switched from the solenoid valve for the water-salt solution - in effect also from the fresh water valve - to the drain valve's solenoid. The inflow ceases and the drain opens. One cubic foot of water begins to flow into the flume. Condition 3 has been reached. About two minutes have transpired since the start of the filling process in the measuring tank.

The swirling entry of the salt solutions facilitates the establishment of a uniform mixture in the measuring tank. A short delay by means of a thermal-delay switch allows this mixing process to continue for a short period before the solution flows into the flume. As it passes out of the measuring tank, probe 3 is uncovered. Nothing happens. As probe 2 is bared the relay in sensing unit 2 is deactivated; however, nothing of consequence happens because the electrical power has been switched from this relay to the drain valve solenoid. This is Condition 4. The draining process continues until probe 1 is uncovered. The relay of sensing unit 1 is deactivated. The power is switched from the drain valve, which then closes, to sensing unit 2 and then to the fresh water valve. The process has come full circle.

A fraction of the measuring tank has been filled with fresh water and the remainder with salt water. The extent of this fraction is determined by the position of probe 3. When the probe is near the bottom of the measuring tank very little fresh water is added before the salt solution is added. A "dense" composite mixture is the result. When probe 3 has been moved to the top of the tank, near probe 4 the fresh water occupies nearly all of the measuring tank. A small remainder will be filled with salt solution. A mixture whose density is only slightly greater than fresh water is the result. The probe is raised an increment (0.100") each time the tank is



$\bar{U}$ = 1.?? cm/sec
D = 5.08 cm
$\mathcal{R}$ approx. ???
$\Delta\rho$/depth = [illegible] = 1.55(10^{-4}) gm/cm



$\bar{U}$ = [illegible]
$\mathcal{R}$ [illegible]
Density [illegible] as above

Figure 45 [illegible]

filled so each charge that flows into the flume is of lower density than the previous one. Thus each layer can be floated upon the liquid already in the flume. A 50 cubic foot tank is used to mix the salt water solution. The salt solution is pumped from this tank in order to speed up the addition of the salt solution to the measuring tank. However, this was a secondary purpose; the primary one was to provide sufficient pressure to cause a rapid mixing of the incoming salt solution with the liquid already in the measuring tank. To achieve this mixing the salt solution is admitted near the top of the measuring tank in a swirling manner. The mixing process is given time to occur by providing a 30-second interval between the cessation of filling and the beginning of the draining of the measuring tank.

A complete cycle for the measuring tank is about 4 1/2 minutes. Each cubic foot of water that passes through the measuring system fills about 1/100 of the flume. Thus the flume can be filled in about 8 hours. A small amount of diffusion produces a continuous density variation.

Floats with mercury switches have been installed at the top of the measuring tank and the flume. Should either of these two containers be filled beyond their intended heights, the floats will raise and tilt the switches. The 110 volt electrical power to the system will be interrupted and the filling process will stop.

While the system that was constructed produced a constant density gradient, others could be created by changing the method by which the probes are raised. If the probes were elevated by a cord wrapped around a drum of varifying diameter, a non-linear density profile would result. Figure A3 shows an experiment in a stratified solution that was obtained with the present system.

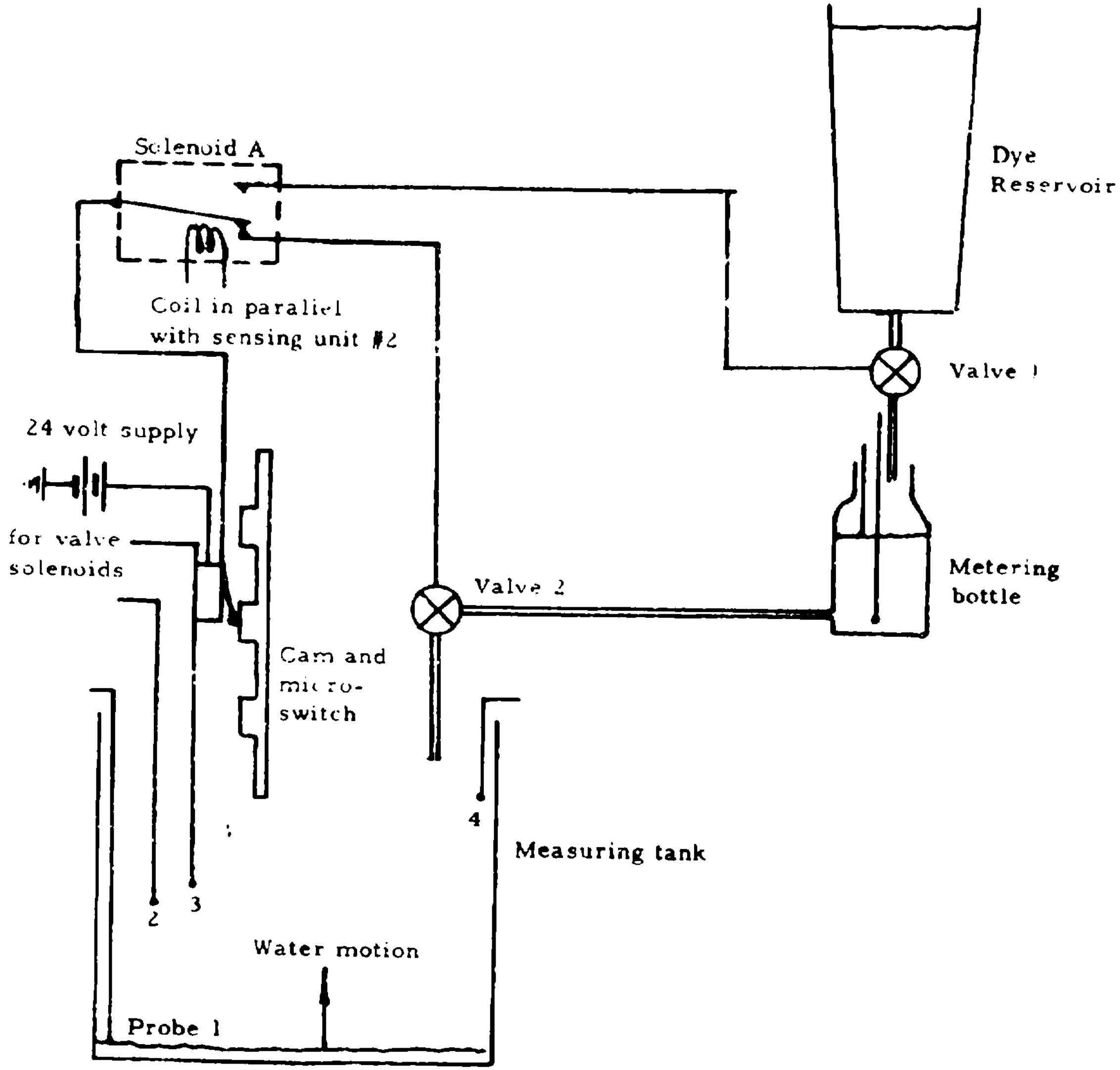


Figure A4

Liquid Level Detector Circuit

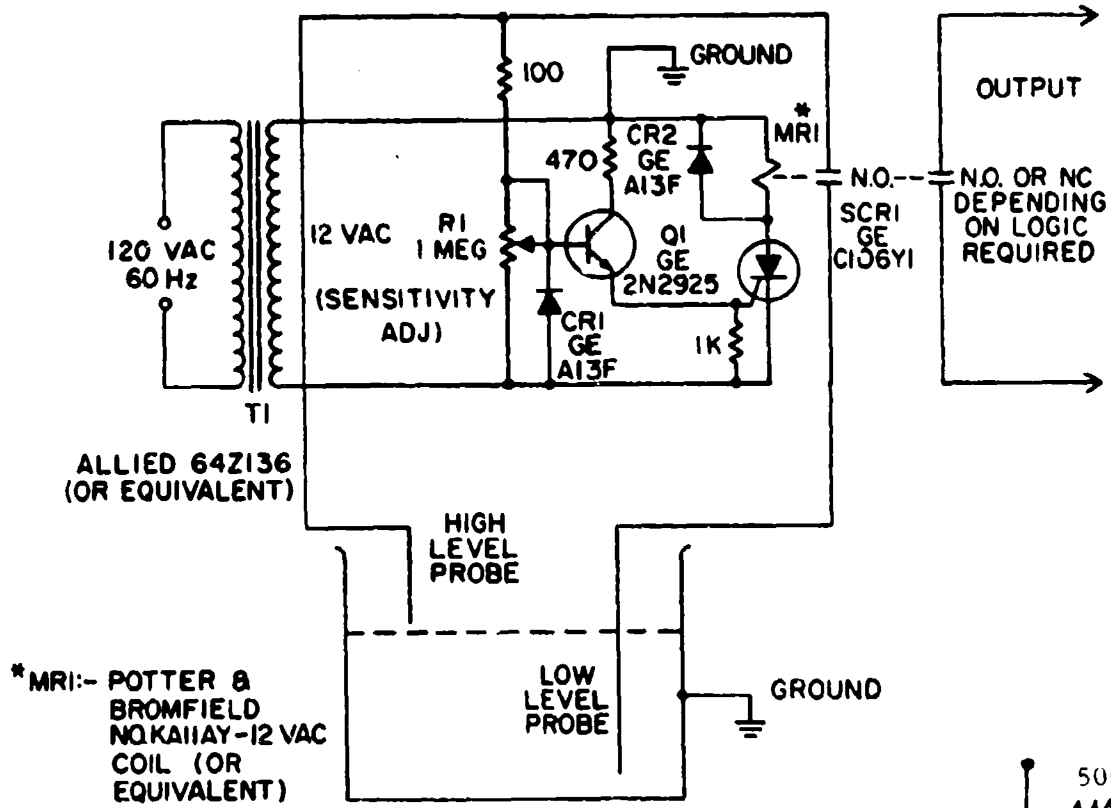
A2.2. Dye-monitoring system

Because the liquid is added to the tank discretely, it is possible to add a small amount of dye to some layers to produce horizontal dye layers in the flume at the completion of the filling period. The system for producing the colored layers is shown in Figure 4. A dye reservoir, a metering chamber, level sensors and solenoid valves complete the system. This was assembled from parts on hand and variations of this scheme could be adopted to fit other equipment that is readily available. Indeed, inexpensive timing motors to operate the valves were anticipated at one time.

If one refers to Figure A4 the method of operation will become clear. Solenoid A is in parallel with the circuit supplying current to the fresh and salt water valves. When this circuit is activated and water first enters the measuring tank, solenoid A closes and power is applied to valve number 2. The metered amount of dye flows into the measuring tank. This takes about 30 seconds. As soon as the lower sensor in the metering bottle is bared, the solenoid in the control unit is dea ivated and the contacts are closed, which should send voltage to solenoid valve number 1. If this valve is activated liquid would flow into the metering bottle from the reservoir. However, because of the delay unit in the circuit powering solenoid A, no power is available for switching to solenoid valve 1 until the metering bottle is empty and the outlet valve is closed. When the switching solenoid A is deactivated, electrical power flows to valve 1 via the solenoid in the control unit. Thus the metering bottle is again charged so that it can add dye to the mixing tank the next time it is filled. This is true provided the microswitch has been closed. This microswitch is elevated with the probes of the mixing system. It rides over a series of cams which have a spacing and breadth appropriate to the dye pattern that is desired in the flume.

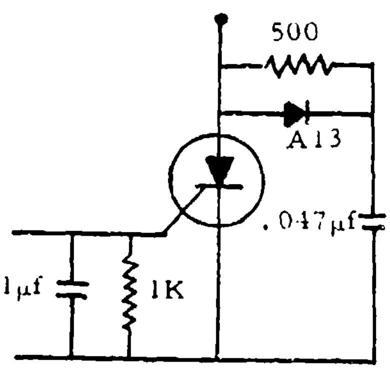
ACKNOWLEDGMENTS

The idea of using a movable probe in the measuring tank was suggested by Professor W. P. Graebel. The efforts of Mr. William Huizenga which led to the isolation of difficulties and their elimination transformed the system from a concept to a reality.



LIQUID LEVEL DETECTOR

(By permission of General Electric Company)



Additional components to suppress solenoid valve induced transients

Fig. B1. Liquid level detector circuit